Clinical Outcomes of Femtosecond Laser–Assisted Implantation of Asymmetric ICRS in Keratoconus With No Coincidence of Topographic and Comatic Axes

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ABSTRACT

PURPOSE: To analyze the clinical outcomes obtained with asymmetric intracorneal corneal ring segments (ICRS) of variable thickness and width in patients with keratoconus, identifying predictive parameters of the final visual outcome.

METHODS: This prospective, longitudinal, non-comparative clinical trial enrolled 35 eyes of 27 patients with keratoconus with a significant difference among corneal topographic and comatic axes. All eyes underwent implantation of AJL-pro+ ICRS (AJL Ophthalmic). Visual, refractive, corneal topographic and aberrometric, and pachymetric changes were evaluated during a 3-month follow-up.

RESULTS: Significant changes were detected at 3 months after surgery in manifest sphere and cylinder, spherical equivalent, overall blur strength, and corrected distance visual acuity (CDVA) ($P < .001$). No losses of two or more lines of CDVA were observed, whereas 94.3% (33) of eyes gained one or more lines of CDVA. Keratometric readings and the magnitude of anterior corneal astigmatism were significantly reduced with surgery ($P < .001$), as well as the levels of corneal coma ($P < .001$) and spherical aberration ($P = .007$). Likewise, a significant change toward less prolateness was observed ($P < .001$). Significant correlations were found among the change in CDVA and preoperative CDVA ($r = -0.532$, $P = .001$), and between the change in primary coma root mean square and the preoperative level of spherical aberration ($r = -0.542$, $P = .001$) and coma root mean square ($r = -0.719$, $P < .001$).

CONCLUSIONS: The implantation of the ICRS evaluated in keratoconus with no coincidence between topographic and comatic axes regularizes the corneal shape and reduces the level of higher order aberrations, inducing a significant visual improvement.

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The surgical options for the management of keratoconus are in constant evolution.[1] During the past two decades, penetrating keratoplasty has gone from a predominant position to being relegated to a last resort treatment. Corneal surgeons currently have a broad number of techniques to treat keratoconus before getting to penetrating keratoplasty. Among the most used is intracorneal ring segments (ICRS) implantation. Although this technique's initial theoretical idea has not changed considerably over the years, the materials, designs, and surgical procedures have experienced a remarkably significant evolution.[2,3] At the same time, the mode of understanding keratoconus through complementary tests has led treatments to focus on new aspects of this pathological condition, such as keratoconus phenotype or aberrometry.[4,5]

The efficacy of ICRS implantation has been widely demonstrated in the peer-reviewed literature.[6] Their use in patients with keratoconus often improves visual acuity, keratometry, and coma, and reshapes the

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cornea.[7] However, despite all of the technological advances in diagnosis, surgical technique, and nomograms, poor and disappointing results with ICRS implantation have been reported in some cases, forcing positional changes in second surgeries and even explantation.[8-10] One possible explanation is that, until now, keratoconus with asymmetric patterns ("snowman" and "irregular croissants," not concordance among topographic and coma axes) was treated with symmetrical ring segments (same thickness and base width across all of the segment). This fact could explain the lack of concordance obtained in these cases between the visual and tomographic results.[11] For this reason, ICRS of constant thickness and base width have been stated to be excellent astigmatic correctors but deficient in the control of coma, which could be fundamental for the acquisition of excellent visual results.[12] This hypothesis has led the scientific community to investigate different variations of ring segment designs, including asymmetric segments.[13-16]

A new type of ICRS (AJL Pro+; AJL Ophthalmic) has been recently tested and approved for its use in the European Community. These ring segments show variations along their arc length in terms of thickness and base width.[17] A pilot study has been conducted to evaluate these asymmetric ICRS (using a technique of mechanical dissection for their implantation), confirming that they are safe and especially effective for controlling the level of primary coma aberration in eyes with mild to moderate keratoconus, showing a discrepancy among topographic and comatic axes between 30° and 105°.[17] The current study also analyzed the visual, refractive, tomographic, and aberrometric results obtained with the use of these new ring segments in patients with the same type of keratoconus, but additionally identifying some predictors of the final visual outcome achievable with these implants.

PATIENTS AND METHODS

PATIENTS

This was a prospective, single-center, longitudinal, non-comparative clinical trial enrolling a total of 35 eyes of 27 patients with keratoconus. All eyes underwent implantation of AJL-pro+ asymmetric ICRS of variable thickness and width (AJL Ophthalmic) in the Clinique Internationale d'Ophtalmologie (Tunis). This study was approved by the Ethics Committee of the institution and was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. All patients provided written informed consent to be included in the study after a careful explanation of its nature, advantages, and risks.

Inclusion criteria for the study were patients 18 years or older, diagnosis of keratoconus according to the standard diagnostic criteria (asymmetric topographic pattern and at least one of the following clinical signs on slit-lamp examination: stromal thinning, conical protrusion of the cornea at the apex, Fleischer ring, or Vogt striae),[18] presence of mild to moderate keratoconus according to the Amsler-Krumeich grading system (grades I to III),[19] inferior-superior asymmetry index of more than 2.00 diopters (D), and a difference among topographic and comatic axes (between 30° and 85°: "duck pattern" or "irregular croissant pattern"; between 85° and 105°: "snowman pattern"). To avoid the potential bias introduced by the correlation between fellow eyes, only one eye was included per patient, except in those cases in which a difference between right and left eyes of more than two grades of the Amsler-Krumeich grading system was present (significant interocular asymmetry). In cases where both eyes were elegible for surgery but with no stage difference, the eye with higher keratometry values and poorer visual acuity was included in the study. Exclusion criteria were severe keratoconus (grade IV, Amsler-Krumeich), previous ocular surgery, active systemic or ocular diseases, ocular media opacity, and pregnancy. No contact lens fitting was prescribed and they were not worn by any patient during the follow-up of this study.

EXAMINATION PROTOCOL

A complete preoperative examination was performed in all cases, including anamnesis, manifest and cycloplegic refraction, corrected distance visual acuity (CDVA), slit-lamp examination, tomographic analysis with the Pentacam HR system (Oculus Optikgeräte GmbH) that included evaluation of corneal topography, aberrometry and pachymetry, infrared pupillometry, corneal topography and aberrometry with the OPD Scan III system (Nidek Co Ltd), and fundus evaluation under pupil dilation. During the postoperative follow-up, patients were examined the day after surgery and at 1 and 3 months after surgery. The integrity of the cornea was evaluated on the first postoperative day with the slit lamp. The other two postoperative examinations included measurement of manifest refraction and CDVA, slit-lamp biomicroscopy, corneal topography and aberrometry, and pachymetry.

RING SEGMENTS

AJL-pro+ ring segments with variable thickness and width are an evolution of classic intracorneal Ferrara rings, having the same triangular cross-section. However, the thickness and width of the base can be modified in these new segments within a predefined range. Specifically, the ring segment model providing an optical zone of 5 mm (arc-lengths of 160° and 210°) presents an apical length of 5.5 or 5.7 mm, a variable base width of 0.60 to 0.80 mm or 0.80 to 0.60 mm, variable thickness from 0.15 to 0.25 mm (clockwise or counterclockwise) or from 0.15 to 0.30 mm (clockwise or counterclockwise), and an orifice of 0.20 mm in diameter in each extreme of the ring. Concerning the ring segment model providing an optical zone of 6 mm, the same possibilities of variation in thickness and base width are available, but the apical length is 6.4 or 6.7 mm. The selection of the most adequate option to implant in each case was made according to the manufacturer's recommendation according to its nomogram (AJL nomogram for AJL-pro+ ring segments), which is based on the developments of Dr. Kammoun. This nomogram has been described in detail previously.[17]

SURGICAL TECHNIQUE

All surgical interventions were performed by the same expert surgeon (HK) using topical anesthesia (two proparacaine eye drops, 10 minutes before surgery). The corneal incision was placed on the steepest meridian according to the topographic map in all cases. The tunnels were created using the Intralase FS 60 femtosecond laser system (Johnson & Johnson Vision). The center of the pupil was marked on the slit lamp and then the vacuum suction ring was positioned onto the eye. The disposable glass lens of the laser system was then applanated to the cornea to fixate the eye. The photodisruption of the femtosecond laser was then initiated, creating a continuous circular stromal tunnel at approximately 80% of corneal depth.

After the creation of the tunnels, ring segments were inserted throughout the incision into the tunnels and centered with the help of a hook. In all patients and eyes (35 eyes), the center of the ring segments was aligned to the flattest meridian of the cornea and all segments were centered in the pupil center. As postoperative prophylactic treatment, topical tobramycin-dexamethasone eye drops were prescribed to be used postoperatively every 6 hours for 1 week. Likewise, a topical lubricant containing polyethylene glycol 0.4% and propylene glycol 0.3% was prescribed to be applied every 6 hours for 1 month.

STATISTICAL ANALYSIS

Data analysis was performed with the commercially available software package SPSS version 22.0 (IBM Corporation). Normality of data samples was evaluated by the Kolmogorov-Smirnov test. The paired *t* test was used to assess the significance of differences between consecutive visits of normally distributed variables. The Wilcoxon test was used for non-normally distributed data instead. The Pearson or Spearman correlation coefficients were calculated for normally and non-normally distributed data, respectively, to evaluate the relationship between different clinical variables evaluated. For the analysis of refractive changes, all spherocylindrical refractions obtained were converted to vectorial notation using the power vector method described by Thibos and Horner.[20] A *P* value of less than .05 was considered statistically significant for all statistical tests.

RESULTS

PATIENTS

Thirty-five eyes of 27 patients (10 men, 17 women) with a mean age of 30.5 years (range: 18 to 55 years) were included in the current study. A total of 13 right (37.1%) and 22 left (62.9%) eyes were included. Concerning the topographic pattern, 30 eyes (85.7%) showed an "irregular croissant" pattern, whereas only 5 eyes (14.3%) showed a "snowman" pattern. One ring segment was implanted in all cases. Ring segments of 5 mm were implanted in 16 patients (45.7%), whereas ring segments of 6 mm were implanted in 19 patients (54.3%). The most implanted arc length was 160° (33 eyes, 94.3%); 210° was only used in 2 eyes (5.7%). The ring segments with progression in thickness from 150 to 300 µm were the most implanted (31 eyes, 88.6%), with the use of ring segments 150 to 250 µm in the remaining cases.

VISUAL AND REFRACTIVE OUTCOMES

The visual and refractive data obtained during the 3-month follow-up in the evaluated sample are summarized in **Table A** (available in the online version of this article). At the last postoperative visit, 3 months after surgery, significant changes were detected in manifest sphere and cylinder, spherical equivalent, overall blur strength, and CDVA ($P < .001$). The percentage of eyes achieving CDVA of 0.30 logMAR or better changed from 20.0% (n = 7) preoperatively to 88.6% (n = 31) at 3 months after surgery (**Figure 1**). At 3 months postoperatively, no losses of two or more lines of CDVA were observed in any case (**Figure 2**). In contrast, 94.3% (n = 33) of eyes gained one or more lines of CDVA (**Figure 2**).

ANTERIOR CORNEAL TOPOGRAPHIC AND ABERROMETRIC CHANGES

Changes in corneal topographic parameters of the anterior corneal surface are summarized in **Table B** (available in the online version of this article). A statistically significant reduction was observed 3 months after surgery in the steepest keratometry, mean keratometry, magnitude of anterior corneal astigmatism, inferior-superior asymmetry index, and surface asym-

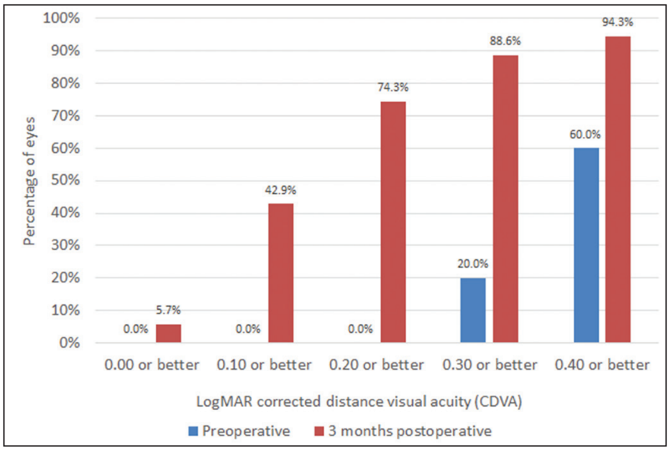

Figure 1. Distribution of preoperative and postoperative logMAR corrected distance visual acuity (CDVA) in the sample evaluated.

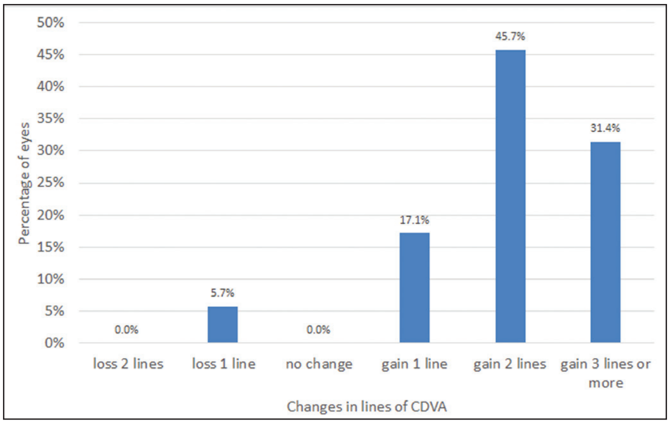

Figure 2. Distribution of the change in lines of corrected distance visual acuity (CDVA) at 3 months after surgery in the sample evaluated.

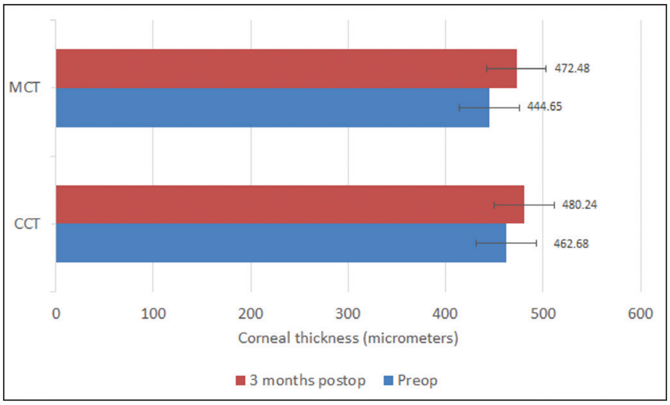

Figure 3. Changes in terms of central (CCT) and minimum (MCT) corneal thickness with surgery in the sample evaluated.

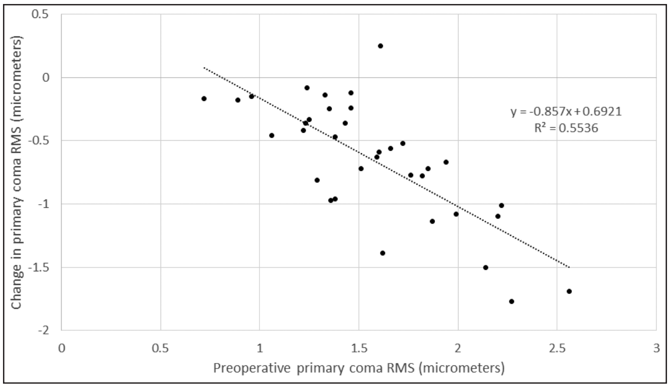

Figure 4. Scatterplot showing the relationship between the change in primary coma root mean square (RMS) with surgery and the preoperative magnitude of primary coma RMS. The adjusting line to the data obtained by means of the least-squares fit is shown.

metry index (*P* < .001). Likewise, a significant change was also observed in anterior corneal asphericity, leading to a lower prolaticity (*P* < .001). Concerning higher order aberrations, a statistically significant reduction was found in spherical aberration (*P* = .007), primary coma (*P* < .001), and irregular (calculated considering all Zernike terms except those corresponding to primary spherical aberration, primary coma and trefoil) root mean square (RMS) (*P* < .001).

PACHYMETRIC CHANGES

Changes in central and minimum corneal thicknesses are represented in **Figure 3**. A statistically significant increase was found in both pachymetric parameters (*P* < .001).

CORRELATION OF VISUAL AND ABERROMETRIC CHANGES WITH BASELINE PARAMETERS

The difference between postoperative and preoperative logMAR CDVA, which represents the visual change induced with surgery, was significantly correlated with the preoperative value of logMAR CDVA (*r* = -0.532, *P* = .001). Likewise, a significant correlation of the difference between the postoperative and preoperative magnitude of primary coma RMS, which represents the change induced with surgery in this parameter, was found with the preoperative values of primary spherical aberration (*r* = -0.542, *P* = .001) and coma RMS (*r* = -0.719, *P* < .001) (**Figure 4**). No significant correlations of the changes induced with surgery in CDVA (*r* = 0.203, *P* = .241) and primary coma RMS (*r* = 0.125, *P* = .476) with preoperative corneal asphericity were found.

COMPLICATIONS

No intraoperative and postoperative complications were recorded in the sample evaluated during the follow-up.

DISCUSSION

The efficacy and safety of a new model of asymmetric ICRS were studied in a sample of 35 patients with keratoconus with specific phenotypes. Of the five distinct categories described by Alfonso,[21] based on the morphological features, eyes with "irregular croissant" patterns with differences between topographic and comatic axes greater than 30° or "snowman" patterns with perpendicular (between 85° and 105°) axes were included. The analysis included visual, refractive, topographic, and aberrometric changes.

Regarding refraction, a significant improvement in almost all parameters was found in the current series. Specifically, the sphere was reduced from a mean preoperative value of -2.98 ± 3.19 D to a mean postoperative value of -1.71 ± 2.48 D ($P < .001$). The astigmatic component, which is one of the most important in keratoconic eyes, changed significantly from -4.14 ± 1.30 D preoperatively to -1.66 ± 0.84 D ($P < .001$) at 3 months after the surgery. Spherical equivalent was reduced in approximately 55% from a mean preoperative value of -5.55 ± 3.33 D to a mean postoperative value of -2.54 ± 2.59 D ($P < .001$). No significant changes with surgery were found in the power vector components of manifest astigmatism. It should be considered that the contribution of posterior corneal astigmatism to total corneal astigmatism and, consequently, to the refractive cylinder may be relevant in keratoconic eyes,[22] limiting or introducing variability in the relationship between changes in anterior and total corneal astigmatism. Despite this fact, blur strength was reduced by 48.6% from a mean preoperative value of 5.55 ± 3.33 D to a mean postoperative value of 2.85 ± 2.42 D ($P < .001$). This parameter is not usually described in other studies, but it is believed that it may inform more precisely about significant changes in refraction.

Different studies have also reported significant changes in manifest refraction components after implantation of ICRS with different designs. Vega-Estrada et al[14] reported the most significant reduction in spherical equivalent up to 7.00 D (from -12.38 ± 3.77 to -5.00 ± 3.26 D) with an asymmetric ICRS of 353°. On the other hand, Kang et al[23] showed a minor reduction from a preoperative value of -7.81 ± 4.94 D to a mean postoperative value of -6.75 ± 4.05 D after 5 years of follow-up in 30 keratoconic eyes implanted with INTACS. In a more recent and similar study, Prisant et al[13] reported a significant change of the spherical equivalent in keratoconic eyes implanted with another type of asymmetric ICRS, with a change from a mean preoperative value of -3.85 D to a mean postoperative value of -1.91 D. Arbelaez and Arbelaez[24] used the same asymmetric ICRS as Prisant et al in duck phenotypes reporting significant reductions of both spherical equivalent and mean sphere. Regarding maximal keratometry, Arbelaez and Arbelaez[24] observed an improvement from a mean preoperative value of 53.70 D to a mean postoperative value of 48.70 D.

Concerning asphericity, a significant change was observed in the anterior corneal surface. The value of Q was halved (from a mean preoperative value of -0.64 ± 0.25 D to a mean postoperative value of -0.37 ± 0.23 D), which can be related to the central flattening induced by the ICRS. These findings were also described by Utine et al[25] in patients with keratoconus treated with symmetric and constant thickness ICRS. The authors concluded that the use of ICRS could resemble the anterior corneal asphericity of those patients to the normal values (-0.26 ± 0.18). Therefore, the excessive prolaticity can be converted to a normal prolate corneal shape after the implantation of ICRS.

Quality of vision is one of the essential parameters in patients with keratoconus. The main actors of this characteristic are corneal and total aberrations. Primary coma and higher order aberrations are the main aberrations degrading the visual quality in keratoconus.[18,19] For many years and in many studies, aberrometric findings were not considered to explain the results of ICRS. Even in recent articles, aberrometric data are not available.[13]

Low changes in primary coma have been described. In patients with keratoconus with no coincident topographic and comatic axes, Alfonso et al[26] found a decrease in coma-like RMS from 0.80 ± 0.53 µm before surgery with constant and symmetric ICRS to 0.61 ± 0.59 µm for a 4.5-mm pupil. Vega-Estrada et al[14] reported a lower change from 4.12 to 3.55 µm in corneal coma-like aberrations in keratoconic eyes implanted with other type of asymmetric ICRS, concluding that further design enhancement was needed to increase the reduction of the asymmetric corneal aberrations. Al-Tuwairqi et al[16] studied two different groups of patients treated with different rings. The group treated with a constant thickness and symmetric ICRS did not change the primary coma. However, coma improved significantly in the patients treated with a 360° ICRS (Myoring). In our study with an asymmetric ICRS with variable thickness and width, primary coma was decreased by 41.4% ($P < .001$), confirming the remarkable efficacy of this design of ring segment to reduce this type of aberration that, according to Piñero et al,[12] had a negative impact on visual acuity due to the distortion that induces.

There are studies that have also analyzed the general impact of all higher order aberrations, not only coma, in eyes implanted with ICRS by means of the analysis of changes in higher order aberrations RMS and other aberrometric parameters. In a study with a large sample of 611 keratoconic eyes treated with constant thickness and symmetric ICRS, Vega-Estrada et al[27] did not detect significant changes in higher order aberrations. Following this line, Pérez-Merino et al[28] did not find any significant decrease in the overall amount of higher order aberrations in a series of 19 keratoconic eyes with symmetric ICRS. However, in our study, irregular higher order aberrations RMS decreased significantly from a mean preoperative value of 4.58 ± 2.48 µm to a mean postoperative mean value of 2.69 ± 1.10 µm. This change represents a reduction of 41.2% in irregular higher order aberrations, confirming the great effect of these new asymmetric rings in reducing this kind of aberration. A coma reduction can be also present in the use of one ring segment compared to symmetrical two segment rings.[12] Future comparative studies should confirm whether asymmetric ring segments can provide a significantly higher reduction of primary coma compared to the use of only one symmetric ring segment.

The improvement of refraction, the topographic regularization, the approach of the Q value to normal values, and the intense decrease in primary coma and higher order aberrations are consistent reasons explaining the excellent visual outcomes obtained with the asymmetric ICRS evaluated here. In our series, CDVA improved from a mean preoperative value of 0.44 ± 0.11 logMAR to a mean postoperative value of 0.22 ± 0.13 logMAR ($P < .001$). Prisant et al[13] reported a significant change in CDVA using another type of progressive thickness ICRS from a mean preoperative value of 0.31 logMAR to a mean postoperative value of 0.21 logMAR. Similarly, Arbelaez and Arbelaez[24] presented a significant improvement of uncorrected distance visual acuity from a mean preoperative value of 0.70 logMAR to a mean postoperative value of 0.22 logMAR in duck phenotypes. In CDVA, the results of Arbelaez and Arbelaez[24] were similar to those reported in this study. Furthermore, in our series, the percentage of eyes that reached a CDVA better than 0.30 logMAR changed from 20% preoperatively to 88.6% after the implantation of the ICRS. Among all patients, 94.3% gained one or more lines of CDVA, which is the highest percentage reported to this date in studies evaluating the outcomes of ICRS. Additionally, no patient lost more than one line of visual acuity.

Finally, no severe adverse events occurred during the follow-up in the current study, confirming the safety of the implant and the technique. The implantation of ICRS assisted by femtosecond laser has shown to be a safe and reproducible technique.[29] No corneal structural alterations were detected, with no significant changes in minimum and central corneal thicknesses during the follow-up.

This study was not without limitations. Different keratoconus phenotypes were included in this study but the results could not be analyzed separately due to the small sample. In addition, postoperative follow-up was only 3 months. It is true that topographic changes have been reported to happen 6 months after ICRS implantation in some studies. However, in other studies, 3 months is considered to be a good end-point to analyze results of ICRS implantation.[30] Regarding this aspect, it is important to mention that, to get the CE marking, the results of the ICRS used in this study were tested at 3 months. The inclusion of both eyes in asymmetric cases may also be a limitation, but it is believed that significant interocular asymmetry reduces considerably the selection bias. Despite these acknowledged limitations, we believe the results of this study are compelling and support the use of this ICRS in asymmetric keratoconus phenotypes.

The implantation of AJL-pro+ ICRS with variable thickness and base width in keratoconus with no coincidence between topographic and comatic axes induces a significant reduction of the prolate shape of the cornea and irregularity, an important improvement in primary coma and higher order aberrations and a significant reduction of refractive components leading to improvement in CDVA. All of these changes are generated with no structural alterations and no severe complications associated. Although this study cannot answer the question of whether asymmetric ICRS with variable thickness and base width enhance vision more than constant thickness ICRS, our results seem to indicate that this alternative can be promising for specific keratoconus phenotypes. Future studies should be conducted to evaluate the long-term outcomes of this type of implant and to optimize further the nomogram of implantation.

AUTHOR CONTRIBUTIONS

Study concept and design (DPP, JÁ, GG); data collection (HK); analysis and interpretation of data (DPP, JÁ, RIB, GG); writing the manuscript (DPP, JÁ, GG); critical revision of the manuscript (HK, DPP, JÁ, RIB, GG); statistical expertise (DPP, JÁ); supervision (RIB, GG)

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TABLE A

Visual and Refractive Changes in the Sample Evaluated

Parameter	Preoperative	3 Months Postoperative	*P*
Sphere (D)			< .001
Mean ± SD	-2.98 ± 3.19	-1.71 ± 2.48	
Median (range)	-1.50 (-14.00 to 0.00)	-1.00 (-11.00 to 1.50)	
Cylinder (D)			< .001
Mean ± SD	-4.14 ± 1.30	-1.66 ± 0.84	
Median (range)	-4.00 (-7.25 to -2.00)	-1.50 (-4.00 to -0.25)	
Spherical equivalent (D)			< .001
Mean ± SD	-5.05 ± 3.42	-2.54 ± 2.59	
Median (range)	-4.13 (-17.00 to -1.75)	-1.88 (-12.50 to 1.25)	
J_0 (D)			.213
Mean ± SD	0.43 ± 1.29	0.14 ± 0.59	
Median (range)	0.34 (-1.78 to 3.59)	0.21 (-1.48 to 1.30)	
J_{45} (D)			.232
Mean ± SD	-0.25 ± 1.71	0.04 ± 0.72	
Median (range)	-1.00 (-2.73 to 2.82)	0.25 (-1.83 to 1.35)	
B (D)			< .001
Mean ± SD	5.55 ± 3.33	2.85 ± 2.42	
Median (range)	4.74 (2.02 to 17.26)	2.30 (0.71 to 12.59)	
CDVA (logMAR)			< .001
Mean ± SD	0.44 ± 0.11	0.22 ± 0.13	
Median (range)	0.40 (0.30 to 0.70)	0.22 (0.05 to 0.70)	

D = diopters; SD = standard deviation; J_0 and J_{45} = power vector components of astigmatism; B = overall blur strength; CDVA = corrected distance visual acuity

TABLE B

Corneal Topographic Changes in the Sample Evaluated

Parameter	Preoperative	3 Months Postoperative	*P*
K1 (D)			.067
Mean ± SD	44.34 ± 1.93	43.75 ± 2.82	
Median (range)	43.72 (41.65 to 49.21	43.77 (32.19 to 48.18)	
K2 (D)			< .001
Mean ± SD	48.66 ± 2.63	46.21 ± 2.31	
Median (range)	48.39 (44.06 to 56.76)	45.76 (40.34 to 49.91)	
Km (D)			< .001
Mean ± SD	46.50 ± 2.15	44.98 ± 2.46	
Median (range)	46.30 (43.30 to 51.36)	44.75 (37.20 to 48.83)	
Asitgmatism (D)			< .001
Mean ± SD	3.55 ± 1.07	2.00 ± 0.94	
Median (range)	3.60 (1.60 to 5.20)	2.10 (0.70 to 5.30)	
I-S (D)			< .001
Mean ± SD	7.04 ± 2.82	4.25 ± 2.50	
Median (range)	6.55 (2.25 to 16.16)	3.78 (0.28 to 12.00)	
SRI			.204
Mean ± SD	1.35 ± 0.21	1.25 ± 0.33	
Median (range)	1.39 (0.86 to 1.80)	1.30 (0.58 to 1.94)	
SAI			< .001
Mean ± SD	2.46 ± 0.93	1.80 ± 1.00	
Median (range)	2.44 (0.91 to 4.85	1.48 (0.64 to 4.43)	
Q			< .001
Mean ± SD	-0.64 ± 0.25	-0.37 ± 0.23	
Median (range)	-0.67 (-1.13 to -0.15)	-0.32 (-1.11 to 0.10)	
Primary coma RMS (μm), 5 mm			< .001
Mean ± SD	1.57 ± 0.41	0.92 ± 0.32	
Median (range)	1.51 (0.72 to 2.56)	0.92 (0.23 to 1.86)	
Primary SA (μm), 5 mm			.007
Mean ± SD	0.78 ± 0.40	0.49 ± 0.38	
Median (range)	0.66 (0.21 to 1.61)	0.38 (0.02 to 1.45)	
Trefoil RMS (μm), 5 mm			.238
Mean ± SD	0.61 ± 0.32	0.55 ± 0.26	
Median (range)	0.62 (0.09 to 1.30)	0.52 (0.18 to 1.23)	
Irregular HOA RMS (μm), 5 mm[a]			< .001
Mean ± SD	4.58 ± 2.48	2.69 ± 1.10	
Median (range)	4.40 (1.44 to 13.16)	2.30 (1.12 to 5.70)	

K1 = corneal power in the flattest meridian; D = diopters; SD = standard deviation; K2 = corneal power in the steepest meridian; KM = mean corneal power; I-S = inferior-superior asymmetry; SRI = surface regularity index; SAI = surface asymmetry index; RMS = root mean square; HOA = higher order aberrations

[a] *The irregular HOA RMS is calculated for all HOA measured excluding primary coma, spherical aberration, and trefoil.*